MATERIALS PROCESSING

ENERGY-CONSERVING REGIMES FOR LASER MACHINING OF GLASS AND CERAMIC MATERIALS

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Analytical relations for calculating the requisite energy density for a prescribed scribing depth are obtained on the basis of a one-dimensional problem of vaporization of an absorbing layer of material with 'prompt' deposition of the energy in a laser pulse. These relations make it possible to determine the energy-conserving scribing regimes for glassy and ceramic materials, possessing volume absorption of laser radiation, irradiated by one or two laser pulses. Energy consumption can be reduced by at most 25 – 35%, depending on the dimensionless parameter χh, by adjusting the machining regime.

Key words: laser machining, vaporization of material, optimal regimes, scribing, glass, ceramic.

Continuous-wave or pulsed lasers are now used to machine glass, ceramic and semiconductor plates [1 – 4]. One method of laser machining of materials is scribing [1]. In this method a continuous channel or row of closely spaced openings is made in the surface of a plate. The final stage of this method of machining is a break, where the plate is divided along the marked contour under a bending load. Laser scribing is a very clean method of machining surfaces and separating plates into individual elements more accurately and efficiently. The machined materials, as a rule, afford volume absorption of the laser radiation. If the properties of the material do not permit machining by thermal splitting [1] or cleavage on the irradiated surface side [5], then scribing is conducted in the vaporization regime.

In [6], where it is assumed that the energy of the laser pulse is deposited 'instantaneously' in the absorbing layer and the thermophysical and optical properties of the plate material are temperature independent, an analytical expression is obtained for the specific (per unit energy input) mass m_{sp} of the vaporized material

$$m_{sp} = \frac{m}{(1-R)W} = \frac{r}{(1-R)\chi W}\ln\frac{(1-R)\chi W}{Q}, \qquad (1)$$

where m is the mass of the material vaporized per unit area; R is the reflection coefficient of the plate material; W is the energy density of the laser radiation; ρ is the density of the plate material; χ is the absorption coefficient of the plate material at the wavelength of the laser radiation; and, Q is the specific energy of vaporization of the plate material.

An investigation of Eq. (1) for an extremum showed that the specific mass of the vaporized material has a maximum at $\dfrac{(1-R)\chi W}{Q} = e$ (e is the base of the natural logarithm) [6, 7], and m_{sp} at the point of the maximum is constant for a particular type of material and equals $(m_{sp})_{max} = 0.368\rho/Q$. The thickness of the vaporized layer is $1/\chi$. If the scribing depth must be greater than $1/\chi$, then N laser pulses with energy density per pulse

$$W = \frac{Qe}{(1-R)\chi} \qquad (2)$$

are required. This gives the minimum energy needed for scribing. Then the depth of the groove in scribing will be $h = N/\chi$.

Since the choice of types of technological lasers is limited and there are many non-metallic materials, situations where the required channel depth for scribing lies in the range $1/\chi < h < 2/\chi$ are possible. For example, for scribing a

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plate of ZHZS12 optical colored glass, whose absorption coefficient at the wavelength 1.064 μm of a ND:YAG laser is $10\ cm^{-1}$ [8], the channel depth 0.14 cm may be required. In such cases one or two laser pulses may be needed to obtain the required channel depth.

The energy density W on the plate surface, the specific energy deposition $E(x)$ due to the absorption of laser radiation by the plate material and the coordinate measured from the surface of the material into the interior are related as

$$(1-R)\chi We^{-\chi x} = E(x). \tag{3}$$

The material will vaporize to depth x if $E(x) \geq Q$. For one laser pulse the energy density required on the surface of the plate to vaporize material to depth h can be calculated from the equation

$$W_1 = \frac{Qe^{\chi h}}{(1-R)\chi}. \tag{4}$$

For two laser pulses, the initial energy density on the plate is determined by Eq. (2) and then, after a layer of material of thickness $1/\chi$ is vaporized, the energy density is

$$W = \frac{Qe^{(\chi h - 1)}}{(1-R)\chi}. \tag{5}$$

The total energy density of the laser radiation in the second case will equal

$$W_2 = \frac{Qe}{(1-R)\chi} + \frac{Qe^{(\chi h - 1)}}{(1-R)\chi}. \tag{6}$$

The dependence of the required energy density on the surface of a plate made from ZhZS12 colored glass on the depth of the channel in scribing with one or two laser pulses is presented in Fig. 1. The calculations were performed using the relations (4) and (6). The initial data for the calculations were taken from [1, 8, 9].

We shall determine the best variant of irradiation that minimizes the energy consumption on machining. For this we divide Eq. (4) by Eq. (6). After simple mathematical transformations we obtain

$$\frac{W_1}{W_2} = \frac{e^{\chi h}}{e + e^{(\chi h - 1)}}. \tag{7}$$

The dependence of the ratio W_1/W_2 on the dimensionless parameter χh in the range $1 < \chi h < 2$ is displayed in Fig. 2. It is evident that for $1 < \chi h < 1.46$ the ratio $W_1/W_2 < 1$. Therefore, in this interval it is expedient to obtain the required channel depth for one pulse with energy density determined by Eq. (4). For $1.46 < \chi h < 2$ the regime with two successive pulses with energy densities determined by Eqs. (2) and (5), respectively, is preferable. For $\chi h =$
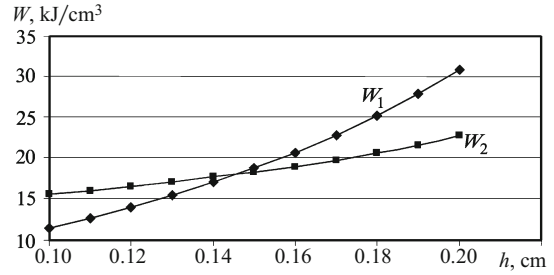

Fig. 1. Requisite energy density W_1 and W_2 on the surface of a plate versus the depth of the channel during scribing by one and two laser pulses, respectively.
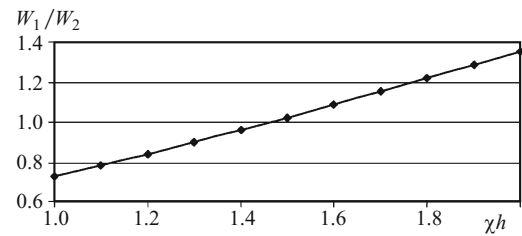

Fig. 2. Energy ratio W_1/W_2 versus the dimensionless parameter χh.

$1.46\ W_1/W_2 \approx 1.0008$. It is evident that the machining regime chosen as a function of the value of the parameter χh makes it possible to decrease the energy consumption by $25 - 35\%$ at the most.

Technological lasers operate, as a rule, in the repetitive pulse regime [1]. For this reason, to obtain a desired channel depth by means of two pulses it is best to first make a channel of depth $1/\chi$ along the contour and then, retuning the laser, pass once again along the same contour with energy density determined by the relation (5).

If the accuracy of the technological equipment is adequate, the machining regime noted above can be used for the entire batch of plates: first, channels of depth $1/\chi$ are obtained on all plates in the batch and then, retuning the laser to the required energy regime, the channel is cut to the required depth for the entire batch of plates.

In summary, analytical relations were obtained for determining the energy conserving regimes for scribing glassy and ceramic materials affording volume absorption of laser radiation in single- and two-pulse passes over a channel. Choosing a machining regime as a function of the dimensionless parameter χh makes it possible to decrease the energy consumption by $25 - 35\%$ at most.

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